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AN EVALUATION OF A PROPOSED SENSOR TO DETERMINE HEAR AT 1/1

THE BASE OF LARGE CALIBER ARTILLERY TUBES(U) HARRY

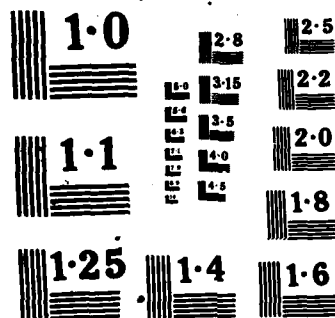
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER HDL-TM-86-5	2. GOVT ACCESSION NO. ADA168 293	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) An Evaluation of a Proposed Sensor to Determine Wear at the Base of Large Caliber Artillery Tubes		5. TYPE OF REPORT & PERIOD COVERED Technical Memorandum
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Donald J. Mary		8. CONTRACT OR GRANT NUMBER(s) PRON: AW-5-TA003-AW-A9
9. PERFORMING ORGANIZATION NAME AND ADDRESS Harry Diamond Laboratories 2800 Powder Mill Road Adelphi, MD 20783-1197		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Element: 63102A
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Materials Technology Laboratory AMXMR-S Watertown, MA 02172		12. REPORT DATE June 1986
		13. NUMBER OF PAGES 30
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES AMS Code: 5-623102.0650011AW HDL Project No: 842585		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Wear sensor Tube wear Tube erosion Torsional impulse		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The use of a sensor to automatically determine the wear of gun tubes is evaluated against the current method, which consists of record keeping and the use of gauges to measure the diametral enlargement of the bore with age. The discussion of one such potential sensor points out the relative complexity of such a device, suggesting that work on this task be discontinued. This evaluation is strengthened by much current literature on gun tubes and by advice and guidelines proffered by several experts in the general field of interior ballistics.		

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1. INTRODUCTION

The purpose of this task* is to explore the development of a sensor (device) which will automatically determine the wear in artillery gun tubes. Wear or erosion at the origin of the rifling in gun tubes may allow the projectile to acquire some linear velocity (free run) before the rotating band engages the rifling. Because of this free run, the outer layer of the rotating band may be sheared off and the projectile will not spin properly. On the other hand, exceptionally high torque may be generated when the rotating band is engraved by the rifling. In either case the fuze may be damaged or not arm. This problem has been especially acute in the 175-mm gun and is now suspected in the 155-mm gun.*†‡

The present method of determining wear requires some record keeping (in the gun book) of rounds fired in the weapon* and the periodic use of star gauges and plug gauges.¹ The method may be of dubious value, however. AMC-PAM-706-252 cautions¹ "that no specific rules on serviceability exist for field inspection. Experience, therefore, becomes the qualifying trait in those who would evaluate the condition of the tube." The successful development of a wear sensor would presumably lead to a definitive means of determining gun tube serviceability. However, such a device may not be a practical solution to this problem, as discussed later.

Currently, the life of a gun tube is measured by the time taken for the tube to reach a state of fatigue in which further firing would lead to catastrophic failure of the tube.² The tube is removed from service before this failure occurs to prevent possible harm to the gun crew. Usually wear or erosion is not considered a gun problem during the life of the tube;² however, if fuze malfunctions caused by tube wear are a reality, then prediction of the onset of these malfunctions would be a useful faculty. Indeed this is the basis of the consideration of a wear sensor in the context of this task.

2. INTERIOR BALLISTICS

All the energy associated with the dynamic parameters during firing comes from the propellant gas. The linear and angular velocities of the projectile result from accelerations of the projectile produced by gas pressure and rifling twist. As the gun tube wears, the origin of the rifling moves forward, i.e., away from the chamber. If the projectile in a worn tube is

¹AMC-PAM-706-252, Engineering Design Handbook, Guns Series, Gun Tubes (February 1964), AD830297.

²ITOP 3-2-829, Cannon Safety Test, US Army Test and Evaluation Command (AMSTE-DA-M), Aberdeen Proving Ground (13 December 1984).

*A. Frydman, Development of Sensor to Determine Wear at the Base of Large Caliber Artillery Tubes, Harry Diamond Laboratories, proposal for D065R, enclosure 2.

†D. E. Waye, letter report, NATO FH70 Cannon Tube Wear Versus Torsional Impulse Study for Artillery Fired 155MM Projectiles, Sandia National Laboratories (1 September 1982).

‡John M. Miller, letter report, Measurement of 155MM Artillery Projectile Interior and Exterior Ballistics, Harry Diamond Laboratories (May 1984).



seated in the same place as when the tube was new, the projectile will undergo a short free run before engaging the rifling. This free run produces a large torsional impulse (high rate of angular acceleration) which may damage the fuze and/or parts of the projectile. If the lands of the rifling have eroded and their diametral separation has increased, the rotating band may be only lightly engraved, followed by the shearing of the rotating band material. The resulting slow spin may not generate sufficient centrifugal force to activate the fuze and properly stabilize the projectile in subsequent flight. It is not clear from the literature how the torsional impulse and shearing of the rotating band are related. Perhaps if such a shearing action occurs, it does so after the torsional impulse. Or, perhaps, the two actions do not occur in the same shot. Furthermore, a worn tube will allow some of the propellant gas to leak past the projectile. Consequently, gas pressure at the base of the projectile will be reduced, decreasing the muzzle velocity and spin of the projectile.

A graphical representation of a torsional impulse is shown in figure 1. The impulse is plotted from Miller's data,* taken from firing an M549A1 projectile from a worn M199 cannon using M203 propellant, zone 8S. The dashed portion of this curve indicates what the angular acceleration would be without the torsional impulse. For a general comparison, a curve from Heppner's "new tube" data³ is presented. The data set selected is No. 401 in his nomenclature, and represents a model XM549 projectile fired from a model M185 cannon using an M30A1 propellant, zone 8. (The M185 and M199 cannons are ballistically similar.†) Miller's gun was in the last quarter of its life and the torsional impulse is characterized by a very rapid rise of angular acceleration. The angular acceleration is increasing at the rate of 2.5×10^8 radians/s². The "normal" rate of increase of angular acceleration in the absence of the torsional impulse is about 7×10^7 radians/s². As the gun tube wear progresses, the torsional impulse begins later in time, indicating that the projectile travels farther before engaging the rifling. A family of such impulses is shown in figure 2.‡ PT09, PT08, and PT20 represent three different NATO FH70 155-mm gun tubes used in the tests discussed by Waye.§ Again, the broad, lower curve represents the angular acceleration due to axial acceleration of the projectile in the absence of the torsional impulse. The ratio of the amplitude of the torsional impulse to the maximum amplitude of the angular acceleration due to axial acceleration increases with tube wear. In figure 2, this ratio varies from about 0.5 to 1.6 for the least and most worn

³Leo D. Heppner, Methodology Investigation, Final Report, Setback and Spin for Artillery, Mortar, Recoilless Rifle, and Tank Ammunition, Aberdeen Proving Ground, APG-MT-4503 (September 1974).

*John M. Miller, letter report, Measurement of 155MM Artillery Projectile Interior and Exterior Ballistics, Harry Diamond Laboratories (May 1984).

†J. Kammerer, 155MM Artillery Weapon Systems Reference Data Book, Large Caliber Weapon System Laboratory, U.S. Army Armament Research and Development Command (May 1980).

‡D. E. Waye, letter report, NATO FH70 Cannon Tube Wear Versus Torsional Impulse Study for Artillery Fired 155MM Projectiles, Sandia National Laboratories (1 September 1982).

tubes, respectively. In summary, the characteristics of the torsional impulse as indicators of gun tube wear are

1. the beginning of the pulse occurs later with increased wear,

2. the ratio of the maximum amplitudes of the torsional impulse to angular acceleration due to axial acceleration increases with gun tube wear,

3. the maximum amplitude of the torsional impulse increases with wear, and

4. the rate of increase of angular acceleration is very large during the rise of the torsional impulse.

These characteristics seem consistent in general, but there are notable exceptions in some of the data.^{4*}† For instance, the parameters of the torsional impulse are affected by the design of the rotating band. A type M549 rotating band allows the projectile, when rammed, to seat further forward into the worn rifling, thus reducing the free run when the round is fired. Conversely, a projectile with the M483 rotating band is not rammed so far forward because of a hump or shoulder on the rear of the band. The projectile with the M483 band experiences a longer free run and a larger torsional impulse. Another type of torsional impulse might occur when the projectile slips back from its seated position onto the propellant bags. This is called a "slammer round."[‡] It is evident that free run in an unworn gun tube could produce a torsional impulse

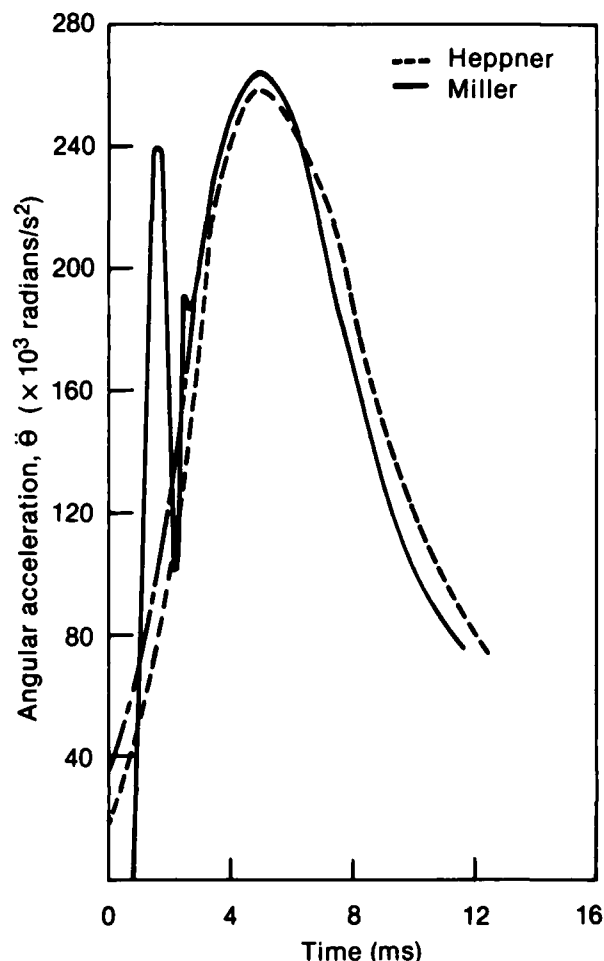


Figure 1. Torsional impulse--spike at beginning of Miller's curve. (Adapted from Miller, unpublished, and Heppner, ref 3.)

⁴N. A. Lapetina, Memo, FG812 Test Report, re APG-M203E2 PIT In-Bore Environment Test Report and Update, Systems Engineering Division, Sandia National Laboratories (4 October).

*D. E. Waye, letter report, NATO FH70 Cannon Tube Wear Versus Torsional Impulse Study for Artillery Fired 155MM Projectiles, Sandia National Laboratories (1 September 1982).

†John M. Miller, letter report, Measurement of 155MM Artillery Projectile Interior and Exterior Ballistics, Harry Diamond Laboratories (May 1984).

‡F. Lueth, US Army Combat Systems Test Activity, Aberdeen Proving Ground, private communication (July 1985).

NATO TUBE TORSIONAL IMPULSE

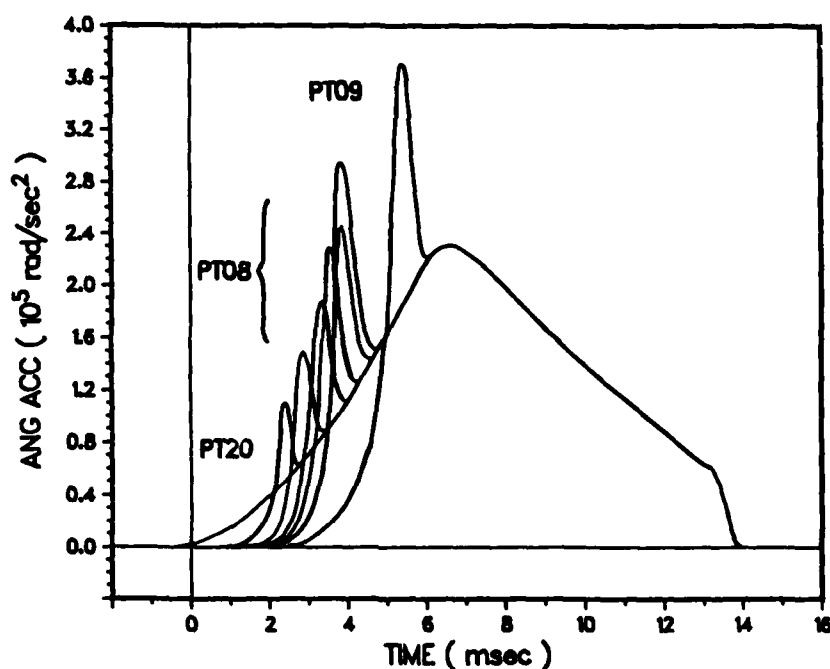


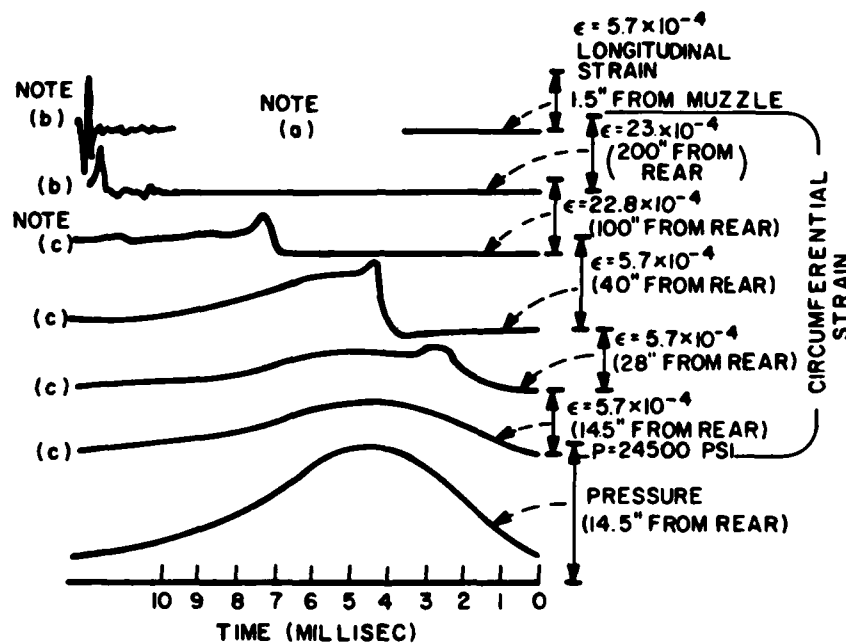
Figure 2. Torsional impulse at different stages of gun tube wear. Both time when impulse begins and maximum amplitude increase with tube wear (from Wayne, unpublished).

or shearing of the rotating band. A "fall back indicator" (FBI) was developed some time ago* to detect a potential slammer round, but the task was cancelled after successful prototype tests. None of the references consulted distinguish between circumstances that cause shearing of the rotating band and those that produce the torsional impulse. Perhaps the nexus between the two is that shearing occurs after the torsional impulse, or there may be no connection at all between the two events. Of course, there are other indicators of wear, and some have been briefly noted elsewhere. They are, as tube wear progresses,

5. decreased muzzle velocity,
6. decreased propellant gas pressure,
7. decreased spin rate,
8. decreased axial acceleration, and
9. decreased force required to engrave the rotating band.

*F. Lueth, US Army Combat Systems Test Activity, Aberdeen Proving Ground, private communication (July 1985).

Some of the parameters change but little and would require precise measurement to determine tube wear. For example, the muzzle velocity for a 155-mm gun will decrease only 7.6 percent throughout the life of the gun tube (as calculated from equations given elsewhere⁵). Reliable determination of tube wear from measurements of muzzle velocity by sensors spaced along the tube might be possible in a controlled environment. But in the subject task, the system is expected to perform satisfactorily in a battlefield environment or after a very long period in storage. Figure 3⁶ indicates that the gas pressure in the gun tube varies with the propellant burning rate and with the expansion of the gas behind the projectile as it moves up the tube. The tube strain, in turn, is dependent upon gas and rotating band pressures and upon wall thickness. Shown are the measured circumferential strains induced in the barrel of the M68, 105-mm gun while firing an M393A1 HEP-T round. The small hump riding on each of the pressure curves marked (b) and (c) is believed to



NOTES:

- (a) LOW AMPLITUDE RINGING REGION
- (b) HIGH AMPLITUDE RINGING REGION - FREQ. ~ 12.5 Hz
- (c) NOISE REGION... FOLLOWED BY LOW AMPLITUDE RINGING - FREQ. ~ 12.5 Hz

Figure 3. Measured chamber pressure and barrel strain in the M68, 105-mm gun (from Davis and Smith, reference 6).

⁵ AMC-PAM-706-150, Engineering Design Handbook, Ballistic Series, Interior Ballistics of Guns (February 1965).

⁶ H. Davis and T. Smith, Proposed Instrument to Measure the Life of Gun Tubes, Harry Diamond Laboratories, HDL-TR-1696 (December 1974).

indicate the passage of the rotating band under each of several strain gauges attached to the outer surface of the gun tube parallel to its axis. Perhaps the muzzle velocity could be obtained from such pulses, but probably not with precision.

3. POSSIBLE SENSORS AND TECHNIQUES

Two possible ways for a sensor to evaluate the gun tube wear come to mind. With the first method, the system records each time the weapon is fired and maintains an accumulative tally (a count-only system). The second method involves periodic monitoring of the weapon's performance; the system measures and quantifies some characteristic of the gun tube or interior ballistics and relates this factor to the condition of the gun tube. Each of the two methods requires, for each shot, a factor that represents the relative erosiveness of the ammunition. Such a factor is called the equivalent full charge (EFC) factor.⁵ (See app A for an empirical formula for deriving the EFC factor.)

Several possible sensors and techniques for evaluating the degree of wear in gun tubes are listed below. No in-depth study has yet been made of these and some may not be practical or even possible.

1. Strain gauges on the outer surface of the gun tube.
2. Microphone near the weapon.
3. Mechanical sensor detecting recoil.
4. Optical (infrared) flash detector.
5. Optical sensor detecting circumferential strain of the gun tube.
6. Air overpressure transducer.

The operational schemes of these sensors are described below.

1. Strain gauges might be used to measure muzzle velocity, chamber pressure, or torsional impulse in a count-only system or a periodic check system. See appendix B for some sample calculations and a comment on detecting torsional strain.

2. A highly directional, insensitive, dynamic microphone near the weapon could be the basis of a count-only system. The microphone would detect the blast noise from the weapon and might be able to operate an electromechanical counter or an electrolytic-cell counter directly.

3. A mechanical device such as a lever arm could actuate a mechanical counter every time the weapon is fired. The lever arm would be moved by the recoil mechanism of the gun. This would be a count-only system.

4. An infrared-sensitive photodetector could be located to detect muzzle flash. An appropriate optical filter would reduce the photodetector response to daylight. This would probably be a count-only system since determination

⁵AMC-PAM-706-150, Engineering Design Handbook, Ballistic Series, Interior Ballistics of Guns (February 1965).

of tube wear by the change in muzzle flash characteristics would probably not be very accurate. Furthermore, flash suppression⁷ would reduce the sensor's effectiveness.

5. An optical interferometric sensor might be able to detect the radial strain or circumferential strain in the gun tube when the weapon is fired. The count of interference fringes passing a slit would be directly related to strain. This device might be used as a periodic check on tube wear by measuring the falloff of chamber propellant gas pressure as the tube ages.

6. An air pressure transducer could be a simple diaphragm device responding to the weapon's noise impulse. Overpressures from 1 to 5 psi occur just behind artillery weapons when fired.⁷ A diaphragm responding to such pressure might produce enough deflection to drive a mechanical counter directly through simple linkage. This would be a very simple count-only system.

4. DISCUSSION AND RECOMMENDATION

Any system (including those mentioned above) requires an input of the ammunition characteristics before each shot to adjust the count or gun parameter measurement to accommodate the EFC factor. However, if in each of these systems, the ammunition data must be entered manually before each shot, the wear sensor no longer competes favorably with the record book and bore gauge methods. A different method* of taking into account the ammunition characteristics (zone charge) would be to store such data in a memory circuit in the wear sensor. For instance, the stored data could be in the form of chamber pressure as related to zone charge. Strain gauges could be used to determine peak chamber pressure each time the weapon is fired. The value of the peak pressure is modified by the accumulative count of the number of rounds fired (adjusted to EFC rounds) since the gun was new in order to account for pressure drop as the tube ages. The pressure drop versus tube age would be a statistically compiled data table also placed in the sensor's memory. The sensor then becomes a device for determining the zone charge (via chamber pressure), standardizing the round by applying the appropriate EFC factor, and keeping an accumulative tally of the number of EFC rounds fired. When the accumulative number of rounds fired reaches the predicted beginning of fuze malfunctions, a warning device of some sort alerts the gun crew.

A device operating on the above principle is characterized by a significant complexity. Yet it supplies only the data presently recorded manually in the gun book--and no more. The device would necessitate engineering concepts satisfying the requirements for (1) a very long life--equal to that of the weapon, (2) retaining a data base which can be updated and from which data can be recalled throughout the life of the weapon, (3) unattended operation, and (4) uncompromising performance in the same meteorological and mechanical environments in which the weapon and its components would be expected to operate. Furthermore, means must be available to (5) calibrate the device as

⁷ AMC-PAM-706-251, Engineering Design Handbook, Guns Series, Muzzle Devices (May 1968).

*H. Curchack, Harry Diamond Laboratories, private communication (August 1985).

needed, (6) determine if calibration is needed, and (7) indicate if the device is malfunctioning or inoperable. Also, the logistics for field or depot servicing, repair, or replacement must be established. With faulty units, it must be possible to extract the entire data base and enter it into the replacement unit. There will certainly be other considerations which would become apparent during the development of the wear sensor, and they are likely to complicate rather than simplify its design.

Any wear sensor operating on such a principle assumes that all gun tubes of the same design and caliber will wear in a predictable manner. If this is so, all one has to do is wear out a few gun tubes to establish the statistical variation of chamber pressure with the number of rounds fired at equivalent full charge. A compilation of such statistics probably has already been done. As mentioned, this would lead to some sort of data base which would recognize the firing of the *n*th round--that round beyond which fuze malfunctions can be expected to occur. However, a literature search has failed to establish the cause of fuze malfunctions in worn gun tubes. Tube wear is inconstant and a formula relating to its progression⁵ does not seem to equate very well to real life. If the *n*th round can be identified as a milestone in the life of the gun tube, the author believes it can be most simply identified in the gun book. Continued work on this task is not recommended.

⁵AMC-PAM-706-150, Engineering Design Handbook, Ballistic Series, Interior Ballistics of Guns (February 1965).

LITERATURE CITED

- (1) AMC-PAM-706-252, Engineering Design Handbook, Guns Series, Gun Tubes (February 1964), AD830297.
- (2) ITOP 3-2-829, Cannon Safety Test, US Army Test and Evaluation Command (AMSTE-DA-M), Aberdeen Proving Ground (13 December 1984).
- (3) Leo D. Heppner, Methodology Investigation, Final Report, Setback and Spin for Artillery, Mortar, Recoilless Rifle, and Tank Ammunition, Aberdeen Proving Ground, APG-MT-4503 (September 1974).
- (4) N. A. Lapetina, Memo, FG812 Test Report, re APG-M203E2 PIT In-Bore Environment Test Report and Update, Systems Engineering Division, Sandia National Laboratories (4 October 1984).
- (5) AMC-PAM-706-150, Engineering Design Handbook, Ballistic Series, Interior Ballistics of Guns (February 1965).
- (6) H. Davis and T. Smith, Proposed Instrument to Measure the Life of Gun Tubes, Harry Diamond Laboratories, HDL-TR-1696 (December 1974).
- (7) AMC-PAM-706-251, Engineering Design Handbook, Guns Series, Muzzle Devices (May 1968).

APPENDIX A.--EQUIVALENT FULL CHARGE FACTORS

As pointed out in the main body of the report, certain parameters relating to ammunition are used to determine a factor that represents the relative erosiveness of the ammunition. Such a factor is called the equivalent full charge (EFC) factor.

An empirical formula that satisfies the experimental results is given in AMC-PAM-706-150, equation (3-60),¹ and is

$$EFC = \left(\frac{P}{P_1} \right)^{0.4} \left(\frac{C}{C_1} \right)^2 \frac{V}{V_1} \frac{E}{E_1} ,$$

where

EFC = equivalent full charge factor,
 P = maximum chamber pressure,
 C = weight of the projectile,
 V = muzzle velocity,
 E = specific energy of the propellant,

and the subscript 1 denotes the value pertaining to the ammunition for which the EFC is chosen to be unity.

¹AMC-PAM-706-150, Engineering Design Handbook, Ballistic Series, Interior Ballistics of Guns (February 1965).

APPENDIX B.--INDICATORS OF GUN TUBE WEAR

All the calculations presented here are based on the M185 and/or M199 cannon.

B-1. TORSIONAL IMPULSE

The peak value of the angular acceleration $\ddot{\theta}$ of Miller's torsional impulse* (see fig. 1 in the main body of the report) is

$$\ddot{\theta} = 240,000 \text{ radians/s}^2.$$

Equation (14) from AMC-PAM-706-150¹ relates $\ddot{\theta}$ with the axial acceleration and velocity as follows:

$$\ddot{\theta} = \frac{1}{R} \left[a \tan \alpha + v^2 \frac{d \tan \alpha}{dx} \right].$$

Rearranging terms,

$$R\ddot{\theta} = a \tan \alpha + v^2 \frac{d \tan \alpha}{dx}$$

where

- R = radius of the bore (3.05 in.),
- α = the angle formed by the tangent to the rifling curve and the x-axis which is parallel to the bore axis (8.92°),
- $\tan \alpha$ = slope of the rifling curve (0.15707),
- a = axial acceleration of the projectile (ft/s²),
- v = velocity of the projectile (ft/s), and
- dx = incremental distance along the bore axis.

Substituting values from Miller in the equation gives

$$\begin{aligned} R\ddot{\theta} &= \frac{3.05}{12} \times 240,000 \\ &= 61,000 \text{ ft/s}^2. \end{aligned}$$

In the same reference,¹ equation (15a) gives the rifling torque, T, as

$$T = \frac{W\rho^2}{gR} \left(a \tan \alpha + v^2 \frac{d \tan \alpha}{dx} \right),$$

where

- W = weight of projectile (96.00 lb),
- g = acceleration due to gravity (32 ft/s²), and
- ρ = polar radius of gyration of the projectile ($\rho = 0.707 R$; $\rho^2 = (1/2)R^2$.)

¹ AMC-PAM-706-150, Engineering Design Handbook, Ballistic Series, Interior Ballistics of Guns (February 1965).

*John M. Miller, letter report, Measurement of 155MM Artillery Projectile Interior and Exterior Ballistics, Harry Diamond Laboratories (May 1984).

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Substituting 61,000 ft/s² for the term in parentheses, the torque becomes

$$T = \frac{96}{32} \times \frac{1}{2} (3.05)^2 \frac{1}{3.05} \times 61,000$$

$$= 279,000 \text{ in.-lb.}$$

This torque induces torsional stresses in the tube of

$$\tau = \frac{Tc}{J} \quad \text{and} \quad J = \frac{1}{2} \pi (r_1^4 - r_0^4) ,$$

and

c = distance from the center to the stress location ($c = r_1 = 5.60 \text{ in.}$),
 T = rifling torque (279,000 in.-lb),
 τ = torsional stress (psi),
 J = polar moment of inertia of the tube cross section,
 r_1 = outer radius of gun tube (5.60 in.),
 r_0 = inner radius of gun tube (3.05 in.),

$$\tau = \frac{2Tr_1}{\pi(r_1^4 - r_0^4)} = \frac{2 \times 279,000 \times 5.60}{\pi(5.60^4 - 3.05^4)}$$

$$= 1108 \text{ psi} .$$

In order to measure torsional strain, strain gauges are usually mounted on the shaft (here, the gun tube) at a 45° angle to the axis of the shaft. As so mounted on the gun tube, the strain gauges would respond only to compression or tension (normal) stress. The relation between maximum shear stress (τ_{\max}) and normal stress (σ_{\max}) is

$$2\tau_{\max} = \sigma_{\max} .$$

Therefore, to calculate the normal strain which will affect the strain gauge when so mounted as described above, we begin with the equation²

$$\sigma = \frac{\epsilon E}{1 + \mu}$$

where

μ = Poisson's ratio (about 0.3 for steel),
 E = modulus of elasticity ($30 \times 10^6 \text{ psi}$),
 ϵ = strain (in./in.),
 σ = normal stress (psi).

In order to calculate the maximum strain from the shear stress, τ_{\max} , the substitution is made for σ :

$$2\tau_{\max} = \frac{\epsilon E}{1 + \mu}$$

²C. C. Perry and H. R. Lissner, The Strain Gage Primer, 2nd Edition, McGraw-Hill Book Company, New York (1962).

or, rearranging terms,

$$\begin{aligned}\epsilon &= 2\tau_{\max}(1 + \mu)/E \\ &= 2 \times 1108 \times (1 + 0.3)/30 \times 10^6 \\ &= 96.0 \times 10^{-6} \text{ in./in.}\end{aligned}$$

It is not clear at this time where the attachment of the gun tube to the recoil mechanism is relative to the origin of the rifling inside the tube. The above derivation assumes that the torsional impulse is generated several calibers beyond the point of attachment, which is probably not the case. Nevertheless, if the value for the strain is representative, the response of a strain gauge to this strain can be computed.

Figure B-1 shows an unbalanced Wheatstone-bridge circuit. R_1 is the strain gauge and R_2 , R_3 , and R_4 are known resistances. For the special case in which all four legs of the Wheatstone bridge have the same nominal resistance R , and for a small change ΔR in the resistance of one leg (R_1), then

$$I_G = \frac{EF\epsilon}{4(R + R_G)}$$

where F is the gauge factor, approximately equal to 2.

The output voltage across the load resistance is

$$E_O = I_G R_G = \frac{EF\epsilon R_G}{4(R + R_G)}$$

The open-circuit output voltage (for $R_G = \infty$) is

$$E'_O = \frac{EF\epsilon}{4}$$

In this computation, assume $R_1 = 350$ ohms and $F = 2$ with a strain $\epsilon = 96 \times 10^{-6}$ in./in. Then, the maximum value of E , the supply voltage, based on a wire strain gauge which can carry 0.030 A without overheating is

$$E = I_1(R_1 + R_4) = 0.030 \times 700 = 21 \text{ V.}$$

Thus

$$\begin{aligned}E'_O &= \frac{EF\epsilon}{4} = \frac{21 \times 2 \times 96 \times 10^{-6}}{4} \\ &= 1008 \times 10^{-6} \text{ V.}\end{aligned}$$

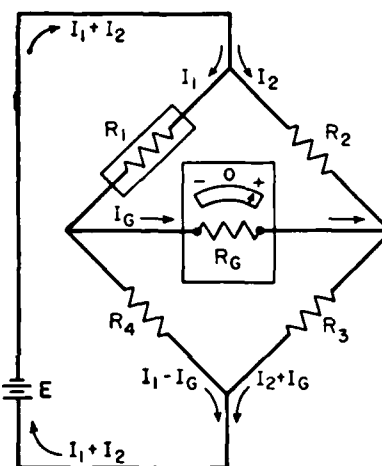


Figure B-1. An unbalanced Wheatstone-bridge circuit (from Perry and Lissner, reference 2).

APPENDIX B

If all four legs of the Wheatstone bridge are strain gauges connected to augment the output voltage, E''_O , across G, then

$$\begin{aligned} E''_O &= 4E'_O = 4 \times 1008 \times 10^{-6} \\ &= 4032 \times 10^{-6} \text{ V} . \end{aligned}$$

This is only 4.0 mV, a very small signal considering the environment with, surely, concomitant ringing and microphonic noise. One scheme, furthermore, would depend on the accurate measure of this signal amplitude which is expected to change by not more than a factor of 3 throughout the life of the gun tube (see fig. 2 in the body of the report). The other scheme would depend on measuring the time after firing that the impulse begins (again, see fig. 2). This time varies from near zero to about 4 ms, a relatively small range of time delays from which to measure the life span of the gun tube. There may be no place on the weapon to get a start (firing) pulse, and a switch or some contacts with accompanying circuitry may have to be added. Of course, any delay between the activation of the firing mechanism and the beginning of propellant burn will have to be determined and periodically remeasured to validate its constancy. Just how this calibration is to be accomplished is not known at this time.

B-2. GAS PRESSURE DROP

The decrease in gas pressure as the tube ages may be a useful indicator of tube wear. Strain gauges on the outer circumference of the gun tube might be able to indicate the chamber pressure drop and, hence, the serviceability of the gun tube.

The maximum gas pressure for Heppner's gun tube in figure B-2 is 44,000 psi. The increase in the outer radius of a thick-wall cylinder (the gun tube) under internal pressure is³

$$\Delta b = p \frac{b}{E} \times \frac{2a^2}{b^2 - a^2}$$

where

a = inner radius (3.08 in.),
b = outer radius (5.60 in. according to Kammerer*),
E = modulus of elasticity (30×10^6 psi),
p = internal pressure (44,000 psi), and
 Δb = increase in outer radius (in.).

Thus

$$\begin{aligned} \Delta b &= 44,000 \frac{5.60}{30 \times 10^6} \times \frac{2 \times 3.08^2}{5.60^2 - 3.08^2} \\ &= 0.007124 \text{ in.} \end{aligned}$$

³R. J. Roark, Formulas of Stress and Strain, 3rd Edition, McGraw-Hill Book Company, New York (1954).

*J. Kammerer, 155MM Artillery Weapon Systems Reference Data Book, Large Caliber Weapon System Laboratory, U.S. Army Armament Research and Development Command (May 1980).

The circumference, C , of the gun tube near the chamber is

$$C = 2\pi b = 35.1858 \text{ in.}$$

The circumference, C' , of the expanded gun tube due to stress is

$$C' = 2\pi(b + \Delta b) = 35.2306 \text{ in.}$$

The change in circumference, ΔC , divided by the original circumference, C , gives the circumferential strain, ϵ , or

$$\epsilon = \frac{\Delta C}{C} = \frac{C' - C}{C} = \frac{35.2306 - 35.1858}{35.1858}$$

$$= 0.001273 \text{ in./in.}$$

$$= 1273 \times 10^{-6} \text{ in./in.}$$

Assuming a single strain gauge is used to measure this strain, the output voltage, E'_0 , is

$$E'_0 = \frac{EF\epsilon}{4} = \frac{21 \times 2 \times 1273 \times 10^{-6}}{4}$$

$$= 13.36 \text{ mV ,}$$

for

$E = 21 \text{ V}$ (the bridge supply voltage),

$F = 2$ (the gauge factor), and

$\epsilon = 1273 \times 10^{-6} \text{ in./in.}$ (the circumferential strain).

To estimate the gas pressure drop as the tube ages, we begin with the gas pressure, P_s , at the base of the projectile, as given by

$$P_s = \frac{Ma}{A} ,$$

where

M = mass of the projectile,

a = axial acceleration of the projectile, and

A = cross-sectional area of the bore.

If we assume the velocity, V , of the projectile increases linearly while in the tube (implying constant axial acceleration--which is not the case) we can substitute in the above

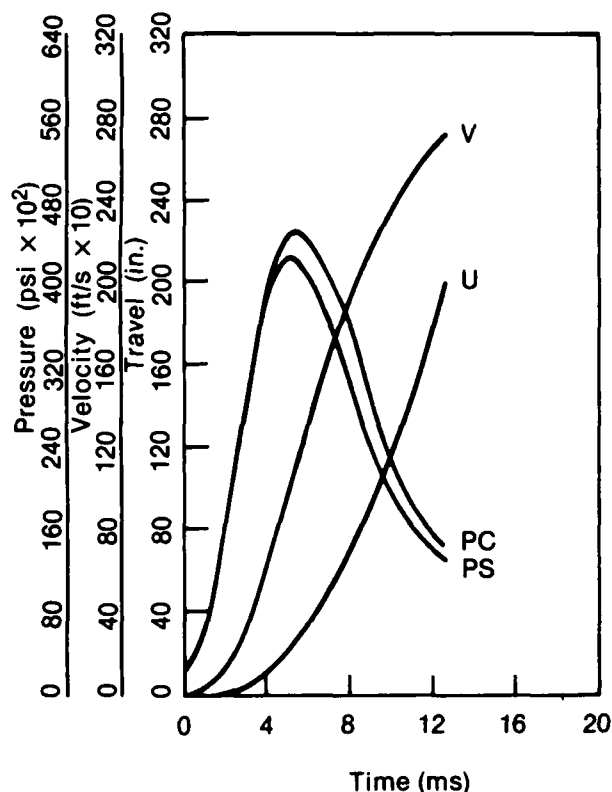


Figure B-2. Parameters, 155-mm howitzer. PC = chamber pressure, PS = projectile base pressure (from Heppner, reference 4).

APPENDIX B

$$\bar{P}_s = \frac{W}{Ag} \frac{12V_m^2}{2S}$$

where

W = weight of the projectile (96.00 lb),
 A = area of the bore (29.810 in.²),
 g = acceleration due to gravity (32 ft/s²),
 V_m = muzzle velocity (ft/s),
 S = travel distance of projectile in the gun tube (200 in.), and
 \bar{P}_s = a fictitious, average, base pressure (psi).

Using Heppner's muzzle velocity (fig. B-2) of

$$V_m = 2700 \text{ ft/s},$$

we obtain

$$\begin{aligned} \bar{P}_s &= 96 \times 2700^2 \times \frac{12}{29.810 \times 32 \times 2 \times 200} \\ &= 22,009 \text{ psi, for a new tube.} \end{aligned}$$

In the case of a worn tube, the muzzle velocity, V_m, can be expected to drop by 7.6 percent or ~204 ft/s, to a value of 2496 ft/s for a tube near the end of serviceability. For this tube, then,

$$\begin{aligned} \bar{P}'_s &= 96 \times 2496^2 \times \frac{12}{29.810 \times 32 \times 2 \times 200} \\ &= 18,809 \text{ psi.} \end{aligned}$$

The percentage drop of gas pressure in a worn-out tube may be

$$\begin{aligned} \Delta \bar{P}_s &= \frac{\bar{P}'_s - \bar{P}_s}{\bar{P}_s} \times 100\% = \frac{18,809 - 22,009}{22,009} \times 100\% \\ &= -14\%. \end{aligned}$$

If this pressure drop is indicative of what actually might be expected, then the strain gauge signal will change only by

$$\begin{aligned} \Delta E'_O &= 13.36 \text{ mV} \times -14\% \\ &= -1.9 \text{ mV} \end{aligned}$$

over the life span of the gun tube.

B-3. MUZZLE VELOCITY DROP

According to AMC-PAM-706-150,¹ equation (2-240), the variation in muzzle velocity for a leaking (worn) gun tube is

$$\Delta V_m = \frac{-V_1 A_1}{A}$$

where

ΔV_m = drop in muzzle velocity (ft/s),
 V_1 = leakage velocity coefficient (about 2000 ft/s),
 A = cross-sectional area of bore (29.810 in.²), and
 A_1 = leakage area (in.²).

In computing A_1 , we note that Heppner⁴ gives A as 29.810 in.² which yields a diameter, d , of the bore of 6.160 in. A gun is considered unserviceable when the diameter of the tube has increased by 5 percent. Thus, the worn diameter is

$$d_w = 6.160 \times 1.05 = 6.468 \text{ in.}$$

The worn cross-sectional area, A_w , of the bore is

$$A_w = \frac{\pi d_w^2}{4} = 32.857 \text{ in.}^2$$

The leakage area, A_1 , is, therefore,

$$\begin{aligned} A_1 &= A_w - A = 32.857 - 29.810 \\ &= 3.047 \text{ in.}^2 \end{aligned}$$

Now,

$$\begin{aligned} \Delta V_m &= -2000 \frac{3.047}{29.810} \\ &= -204 \text{ ft/s} \end{aligned}$$

For an actual muzzle velocity, V_m , of 2700 ft/s (see fig. B-2)

$$\begin{aligned} \% \Delta V_m &= \frac{\Delta V_m}{V_m} \times 100\% = \frac{-204}{2700} \times 100\% \\ &= -7.6\% \end{aligned}$$

¹AMC-PAM-706-150, Engineering Design Handbook, Ballistic Series, Interior Ballistics of Guns (February 1965).

⁴Leo D. Heppner, Methodology Investigation, Final Report, Setback and Spin for Artillery, Mortar, Recoilless Rifle, and Tank Ammunition, Aberdeen Proving Ground, APG-MT-4503 (September 1974).

APPENDIX B

B-4. COMMENTS

The calculation of torsional strain in section B-1 led to a very small signal level. Indeed, the author could find no evidence of anyone ever measuring torsional strain with strain gauges on the outside of a gun tube of the calibers discussed in the report.

TOP 3-1-006 presents many practical suggestions relating to the use of strain gauges to measure dynamic strains that occur during weapon firing.⁵ A typical measurement accuracy of ± 2 to 5-percent full scale is stated. Such accuracy may approach the total variation due to wear over the life of the gun tube of some of the parameters discussed above, e.g., pressure drop and velocity drop.

⁵TOP 3-1-006, Strain Measurement—Unidirectional, US Army Test and Evaluation Command (DRSTE-AD-M), Aberdeen Proving Ground (20 April 1983).

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